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13 ABSTRACT (Maximum 200 words)

The work carried out under this grant has been the investigation of thin films and single crystals of the layered cuprate high-temperature superconductors, as well as other model systems. A primary objective in the program was the development of a better understanding of the limits of the occurrence of superconductors with high transition temperature (above liquid nitrogen temperature). The work is thus composed of an empirical part that searches for superconductivity by similarities and chemical guidance as well as critical tests for various theories of the high-Tc mechanism.

Another aspect of the program was to study the superconducting and normal state properties in applied magnetic fields. In particular we studied the coupling between the Cu-O layers in superlattices. We employed the artificially layered superconductor/insulator system of MoGe/Ge which have in-plane and out-of plane anisotropies which bracket those found in the layered cuprates model system.

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Final Report

GRANT AFOSR-91-0145

Period of 1/15/91 to 11/14/93

P.I. A. Kapitulnik and T.H. Geballe

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P.I.: A. Kapitulnik and T.H. Geballe

I. Introduction

The work carried out under this grant has been the investigation of thin films and single crystals of the layered cuprate high-temperature superconductors, as well as other model systems. A primary objective in the program was the development of a better understanding of the limits of the occurrence of superconductors with high transition temperature (above liquid nitrogen temperature). The work is thus composed of an empirical part that searches for superconductivity by similarities and chemical guidance as well as critical tests for various theories of the high- T_c mechanism.

Another aspect of the program was to study the superconducting and normal state properties in applied magnetic fields. In particular we studied the coupling between the Cu-O layers in superlattices. We employed the artificially layered superconductor/insulator system of MoGe/Ge which have in-plane and out-of plane anisotropies which bracket those found in the layered cuprates model system.

II. Accomplishments

1. It has been found that suitable buffer layers can be employed which permit the growth of device quality of YBCO films on Si. Epitaxial YBCO films were grown on Si (100) using an intermediate buffer layer of yttria-stabilized zirconia (YSZ). The two compounds were deposited sequentially via an entirely *in situ* process using pulsed laser deposition. There is a large difference in thermal expansion coefficients between silicon and YBCO results in strain at room temperature. Thin ($< 500\text{\AA}$) YBCO films are unrelaxed and under tensile stress with a distorted unit cell. Ion channeling reveals a high degree of crystalline perfection with a channeling minimum yield for Ba as low as 12%. The normal state resistivity is $250\text{--}300\ \mu\Omega\ \text{cm}$ at 300K; the critical temperature, T_c ($R = 0$), is 86-88 K with a transition width (ΔT_c) of 1 K. Critical current densities of 2×10^7 at 4.2 K and 2.2×10^7 at 77 K have been achieved. Noise measurements indicate that these films are suitable for use in highly sensitive far infrared bolometers.

2. We constructed a new apparatus to search for superconductivity that exhibits broken time-reversal symmetry. The apparatus has been used to test the theory that superconductivity in the cuprates arises from a new type of ground state that spontaneously breaks time reversal symmetry. This theory is based on the concept that in two spatial dimensions, one can obtain not only quantum ideal Bose and Fermi gases, but also quantum ideal gases of new types of particles that interpolate between those two extremes, hence obeying fractional statistics. Those particles are known generically as anyons. It was first pointed out by Laughlin and co-workers that these gases form superfluids, and become superconductors if the anyons are electrically charged. Thus, similar to a magnetic material, an anyon superconductor will exhibit a spontaneous Hall effect and magneto-optical effects. Polarized light that goes through such a sample will exhibit a non-reciprocal rotation of polarization equivalent to the Faraday effect. Similarly, in reflection, one expects to see an effect resembling the polar Kerr effect.

Previous attempts made by several laboratories failed to provide convincing evidence that these observed positive results were not spurious, in large due to the strong linear birefringence of all the high- T_c cuprates. In order to overcome all those complications and at the same time to achieve measurement with very high accuracy, we constructed a new apparatus that is based on the Sagnac loop. There, two linearly polarized counter-propagating beams are brought to interfere after exiting the loop. In absence of an effect that breaks time reversal symmetry, the interference is constructive and no effect will be detected. However, in the presence of an asymmetry between the two beams, say due to broken time reversal symmetry, there will be a phase shift that can be recovered in an interferometric way. This Sagnac magnetometer is a new invention that was first demonstrated in the measurements of the absence of a Faraday rotation in high quality YBaCuO films. The microstructure of films is however very complicated and the possibility of breakdown into small domains that could reduce the signal in a dramatic way. Since there are no true single crystal films, we have devised a scheme to cleave BiSrCaCuO single crystals and make free standing films as thin as 600 Å. We have performed magnetic measurements to verify the quality of the crystals after the cleaving. No degradation was observed. Cleaved samples were then put onto TEM grids and placed on the sample holder of the Sagnac magnetometer. The optical measurements reveal no nonreciprocal circular birefringence to a sensitivity of 5-10 μ rad. Data was taken in transmission at 1060 and 670 nm wavelength from 20 to 300 K. The latter is a very important result since it measures the non reciprocal effect in a wavelength close to 633 nm, which is the wavelength of the Dortmund experiments that reported large effect including on samples similar to

ours. Our result therefore points to the fact that the previous experiments measured some spurious effects.

3. We have developed a technique to measure magnetization for samples with strong hysteresis in their magnetic properties. Conventional methods, and in particular commercial SQUID magnetometers are useless at high fields because the sample has to traverse through a pick up coil that is arranged in a gradiometer configuration. The inhomogeneous magnetic field induces flux trapped in the sample and thus field cooled measurements are impossible. This can be corrected by using a sample stationary in a SQUID loop but again, this can be done for low fields.

Our solution to the problem is an ultra-sensitive thin film Hall probe, made of low carrier density and high mobility two dimensional electron gas systems, similar to samples used for the study of quantum Hall effect. When high- T_c film is attached to a quantum Hall sample, the measured Hall effect will reflect the magnetic field at the surface of the sample. Knowing the applied magnetic field and the B field at the surface of the film, we can calculate the magnetization M . With the advancement of 2D electron gas samples that can be made with very low carrier density and very high mobility, we achieved a sensitivity of $\sim 2\text{mG}/\text{Ohm}$.

4. We have developed a method for growing superlattices of the layered cuprates with the conducting planes perpendicular to the substrate. We have used this capability to investigate the magnetic field dependence of the superconducting transitions of epitaxial a -axis oriented superlattices of $\text{YBa}_2\text{Cu}_3\text{O}_7/\text{PrBa}_2\text{Cu}_3\text{O}_7$. In fields up to 8 T which are parallel to the substrate (and the superlattice layering), the transitions are insensitive to field for the first decade of decrease of the normal state resistance. We have been unable to find a satisfactory scaling relationship for the characteristic temperature below which field dependence dissipation occurs. When the field is applied perpendicular to the substrate the measured activation energy is found to vary with the thickness of the PrBCO layers out to 480 Å for YBCO layers which are kept at 48 Å. The surprisingly long decoupling length of 480 Å cannot be quantitatively explained in terms of magnetic coupling. The activation energy is logarithmically dependent upon field and is consistent with the collective pinning model of Feigel'man et al.

4 b. Multilayers of MoGe/Ge were constructed to study the vortex state in model systems for high- T_c superconductors. We have studied the linear and nonlinear electrical transport in perpendicular magnetic fields of very thin amorphous $\text{Mo}_{79}\text{Ge}_{21}$ superconducting films. At low fields, there is an apparent

barrier to vortex motion away from the sample edges. In cases where the vortex motion is not substantially affected by the sample edges, manifestly collective activated behavior is observed. We relate the field dependence of the observed activation energies to possible mobile configurations of vortices.

For thicker films, we have measured the ac penetration depth in the presence of a perpendicular magnetic field. We have found an anomaly in the ac response of the vortex lattice at a characteristic temperature below the $H_{c2}(T)$ line. The field and frequency dependence of this anomaly is found to be consistent with a Kosterlitz-Thouless type melting of the two-dimensional vortex lattice. Moreover, we observed a crossover in the frequency dependence which suggests that the vortex lattice remains disordered on long length scales below the melting temperature.

5. The existence of spontaneous polar Kerr rotation in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ single crystals and $\text{YBa}_2\text{Cu}_3\text{O}_7$ thin films was tested using our newly developed Sagnac interferometer. Observation of this effect would be strong evidence that the superconductivity in the high- T_c cuprates is described by a theory that predicts broken time-reversal symmetry. We have analyzed the Kerr effect for both a spatially fluctuating component (anticipating domains) and absolute offset. Neither effect was observed within the sensitivity of the apparatus. The drift of the apparatus sets an upper limit for the offset component at $10\mu\text{rad}$. The noise places an upper limit of $3\mu\text{rad}$ on the standard deviation of the spatial fluctuations of the effect.

III. Publications under this program (full or partial support)

1. "Measurement of the Spontaneous Polar Kerr Effect in $\text{YBa}_2\text{Cu}_3\text{O}_7$ and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$," by S. Spielman, J.S. Dodge, L.W. Lombardo, C.B. Eom, M.M. Fejer, T.H. Geballe, and A. Kapitulnik, *Phys. Rev. Lett.* **68**, 3472 (1992).
2. "Observation of Kosterlitz-Thouless-Type Melting of the Disordered Vortex Lattice in Thin Films of a-MoGe," by A. Yazdani, W.R. White, M.R. Hahn, M. Gabay, M.R. Beasley, and A. Kapitulnik, *Phys. Rev. Lett.* **70**, 505 (1993).
3. "Two step transition towards the reversibility region in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8-\delta}$ single crystals," by H. Pastoriza, F. De la Cruz, D.B. Mitzi, and A. Kapitulnik, *Phys. Rev. B* **46**, 9278 (1992).
4. "A-axis-oriented $\text{YBa}_2\text{Cu}_3\text{O}_7/\text{PrBa}_2\text{Cu}_3\text{O}_7$ superlattices: growth and transport properties" by J.M. Triscone, C.B. Eom, Y. Suzuki and T.H. Geballe, *Journal of Alloys and Compounds*, **183** 224-240, (1992).

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5. "Vortex-Antivortex Crystallization in Thin Superconducting and Superfluid Films" by M. Gabay, A. Kapitulnik, Phys. Rev. Lett. 71, 2138 (1993).

6. "High-Resolution Magneto-optic Measurements with a Sagnac Interferometer" by A. Kapitulnik, J.S. Dodge, and M.M. Fejer, Invited Paper to the 38th Annual Conference on Magnetism and Magnetic Materials, Minneapolis, Minnesota, Nov. 15-18, 1993, to be published in J. Appl. Phys. (1994).

7. "Microstructure and Transport Properties of Various 90° Grain Boundaries in YBa₂Cu₃O₇ Thin Films" by C.B. Eom, J.M. Phillips, A.F. Marshall and T.H. Geballe, Submitted to "Interface Science" Oct. 1993 for publication release of May 1994.

8. "Anisotropic transport properties of in-plane-aligned a-axis YBa₂Cu₃O₇ films" by Y. Suzuki, D. Lew, A.F. Marshall, M.R. Beasley, Phys. Rev. B, 48, 10642 (1993).

9. "Searching for Superconductivity Above the Present Limit", by T.H. Geballe, Physica C 209, 1993.

Students Receiving Degrees Present Position

Steven Spielman Miller Fellow UCB
Thesis Title: "Optical Tests For Broken Time-Reversal Symmetry In the Cuprate Superconductors" June 1992

David Fork Xerox PARC (Staff Member)
Thesis Title: "The Heteroepitaxial Growth of YBCO and Other Metal Oxides On Silicon and GaAs Pulsed Laser Deposition" January 1992

David Mitzi IBM Yorktown (Staff Member)
Thesis Title: "Growth and Properties of Oxygen and Ion Doped Bi₂Sr₂CaCu₂O₈+g Single Crystals" Sept. 1990

Chang-Boem Eom Duke University (Assistant Professor)
Thesis Title: "Synthesis and Properties of High T_c Superconducting Thin Films and Multilayers Grown *in situ* by 90°" July 1991

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